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PERFORMANCE ASSESSMENT OF DIGITAL HYDRAULICS IN A QUADRUPED ROBOT LEG

Shuang Peng, David T. Branson III, Emanuele Guglielmino, Thiago Boaventura, and Darwin G. Caldwell
Department of Advanced Robotics
Istituto Italiano di Tecnologia
via Morego, 30
16163 Genova, Italy

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ABSTRACT

This paper presents an investigation of the performance of digital hydraulic actuation in robot applications. The research compares two different hydraulic actuation systems, utilizing servo and digital hydraulic valves, developed to drive one leg of a hydraulic quadruped robot (HyQ). Comparisons between the two systems for position tracking, required flow rate and system efficiency are discussed. Results show that digital hydraulic systems can be a valid alternative to servo valves in terms of position tracking, and show that digital valves can greatly improve system performance in the form of reduced required flow rate and improved overall system efficiency.

INTRODUCTION

Electric motors are the typical actuation method employed in robotics because of their low cost and the large availability of sizes and specifications. However, although electric motors are simple and accurate to control their performance is limited by several factors. Including that their available torque is small relative to their size and weight, and they often require a gearbox and gears that introduce backlash and reduce drive efficiency.

Alternatively, hydraulic actuators have a relatively faster response, and a higher force/torque-to-weight ratio than electric actuators. Hydraulic actuation has been employed in a wide range of robotic systems, namely the exoskeleton system BLEEX [1-2], Raytheon SARCOS [3], SARCOS hydraulically actuated humanoid robot CB [4], legged robots Kenken [5], BigDog [6-8], Petman [9], KITECH and POSTECH Korean Quadruped Robot [10] and the hydraulic quadruped HyQ [11-13].

A typical hydraulic drive consists of a pump driven by an electric motor or an engine, relief valve, oil tank, valves, linear cylinders and/or rotary hydraulic motors, and utilizes mineral or synthetic oil as the power transmission medium. Typically the power supplied by the pump is used to drive the load. However, in traditional servo valve configurations a significant part of the pump output is lost across the valves used for flow control due to internal valve leakage and throttling losses. This can lead to a dissipation of over 50% of the input power from the pump [14]. Conversely electric actuation achieves a much greater efficiency thanks to the use of power electronics.

In hydraulic systems the efficiency of the actuation defines the flow requirements and hence the pump size. This in turn defines the main onboard motor/engine and its respective power supply medium (battery, petrol tank, etc) size. This further affects the overall weight of the robot, and hence its autonomous run time and dynamic performance. The need to go beyond the use of the less efficient servo valve based flow control is leading to the design of new hydraulic actuation systems requiring both high dynamics and light weight.

Researchers have proposed different methods to address the problem of efficient hydraulic actuation. Williamson et al. proposed displacement-controlled actuation where a variable displacement pump controls the movement of a single or double-rod cylinder. This design successfully eliminated metering losses and recovered power when the pump acted in motoring mode [15], but added large amounts of weight to the system. Cleasby and Plummer employed a variable capacity hydraulic pump to transmit fluid from the pump to the cylinder through a digital on/off valve. Accumulators were then used to collect and discharge high pressure oil when the actuator retracted [16]. However, this method results in higher weight and cost of the system due to the added components.

In a servo valve, ports are separated from each other by a gap between the spool and the valve body. The spool moves continuously and precisely to provide the required flow to the system. The width of the gap between the spool and valve block is carefully designed as a tradeoff between internal leakage and dynamic requirements of the valve. Hence, it is impossible to make a servo valve without leakage.

From an efficiency viewpoint it is better to use a valve with as little leakage as possible. Digital valve technology is considered a feasible and interesting route to be pursued [17 - 19]. A typically digital on/off valve design is poppet-type and the valve is designed in a way that the poppet moves to block flow path when the valve is closed. Therefore sealing is enhanced and internal leakage is much lower with respect to that of a servo valve. Hence replacing servo valves with digital valves can be an effective way to improve system efficiency by reducing internal valve leakage. This increase in system efficiency would then allow for a reduction in pump/motor size.

During the last decade, digital hydraulics has experienced a very rapid development, and a large number of configurations have been investigated with each trading off between quantities of required valves, performance and controllability [20]. The most common one is composed of four DFCUs (Digital Flow Control Units), as shown in Figure 1 and considered in this work [18].

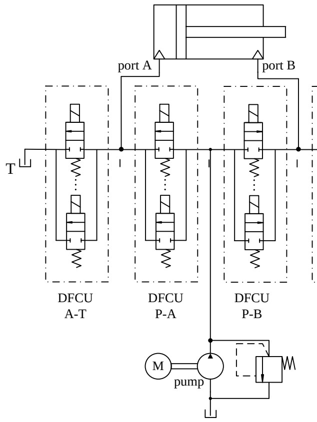


FIGURE 1 - CONFIGURATION FOR DIGITAL FLOW CONTROL UNITS (DFCU)

This paper focuses on analyzing the performance of a digital hydraulic actuation system for a robotic leg of the quadruped robot HyQ and comparing it to a traditional servo valve system. The motion of the leg was simulated to evaluate position tracking, required flow rate and efficiency in both the digital and servo hydraulic systems. Initial experimental comparisons of the hydraulic system on a sliding mass test rig are also compared.

This paper is organized as follows. First general information about HyQ robot is presented, and a 2-D model for a single leg introduced. Next, a description of the different hydraulic systems, servo and digital valves, is made, and finally the model is used in a simulation with the 2-D leg to evaluate performance of the systems.

NOMENCLATURE

A_1	Piston area
A_2	Rod area
F	External load force
i	Differential current input to servovalve
K_1	Servo valve sensitivity to input current
K_2	Pressure feedback gain
N	Number of locomotion cycles
P_1	Pressure in the piston side cylinder chamber
P_2	Pressure in the rod side cylinder chamber
P_{min}	Minimum pressure value
P_{max}	Maximum pressure value
P_L	Pressure drop through the load
P_S	Pump supply pressure
Q	Flow rate of the system
Q_{rated}	Rated flow rate of servovalve
Q_{Leak}	Leakage flowrate of servovalve
Q_L	Load flow rate
Q_S	Supply flow rate
Q_{SV}	Valve required flow rate
Q_1	Flow rate at cylinder piston side
Q_2	Flow rate at cylinder rod side
T	Time
v_{ref}	Reference speed
x_{valve}	Valve spool displacement
x	Cylinder stroke displacement
θ_1	Angular position of the hip
θ_2	Angular position of the knee
ΔP	Pressure drop through the valves
ΔP_{min}	Minimum pressure drop through the valves
ΔP_{max}	Maximum pressure drop through the valves
τ	Time constant of the pressure feedback
ω_n	Equivalent servo valve natural frequency
η	System efficiency

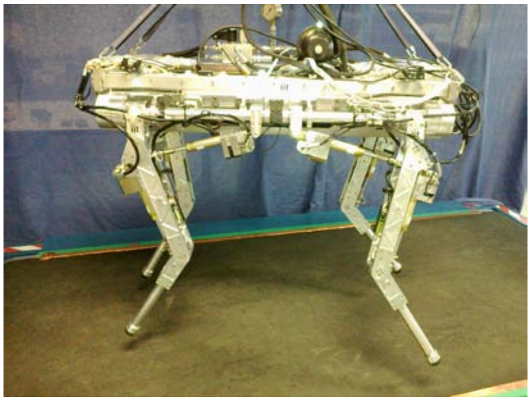


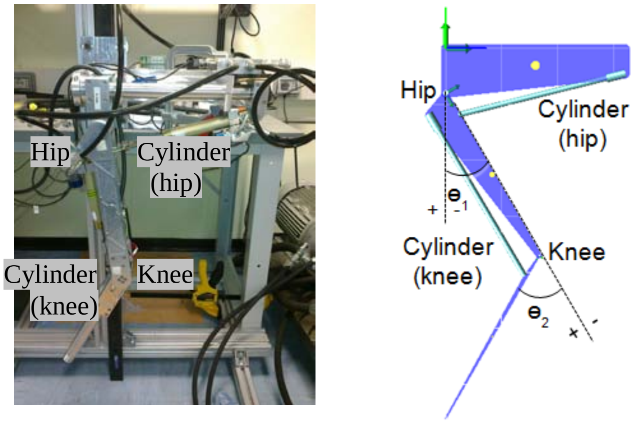
FIGURE 2 - PHOTO OF HYQ

HYQ ROBOT

The hydraulic quadruped robot, HyQ, is a highly dynamic robot that can perform running, jumping and hopping motions (Figure 2). Its overall dimensions are 1.0m×0.5m×0.98m (L×W×H), and the total weight is 90kg. Hydraulic power is supplied from a central pump in the body of the robot, and hydraulic actuators are used to provide power to the joints to achieve dynamic motions (walking, trotting, running and jumping). Further details and parameters can be found in [11].

Framework of HyQ Leg

Each leg of the HyQ robot contains three degrees of freedom (DOF). Hip rotation is actuated by an electrical motor and is not considered in this research. The remaining DOFs for extension/retraction at the hip and knee joints are powered by linear hydraulic actuators. Figure 3(a) shows a picture of the experimental leg test set up, and Figure 3(b) presents the model representation of the leg. Where the blue blocks are the rigid components and joints of the leg, and the green blocks represent the hydraulic actuators. When the leg stretches to its full length both actuators will extend, increasing the angle of the hip and knee joints. Through control of these two actuators, and in combination with the other legs, the HyQ robot is capable of dynamic motions across variable terrains.

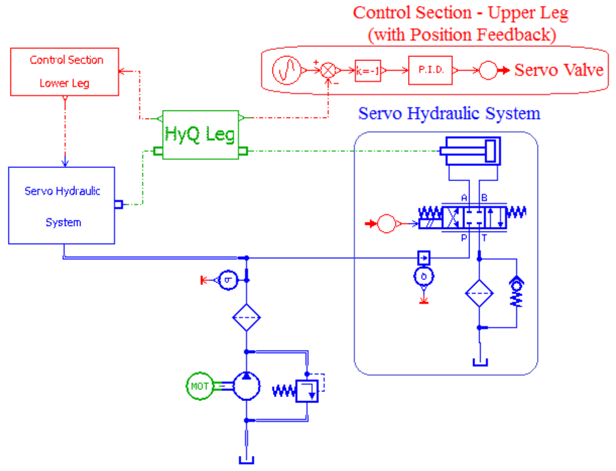


(a) Photo of the single leg (b) 2-D model of the single leg

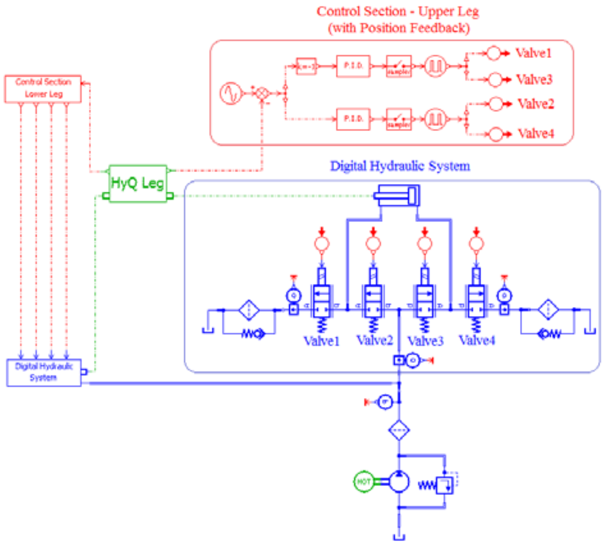
FIGURE 3 - HYQ ROBOT LEG

HYDRAULIC MODEL

In HyQ, each leg has an almost identical structure, and hence have the same capacity for locomotion and dynamic performance. Therefore, this paper aims to investigate the characteristics of the hydraulic actuation system in a single leg in the knowledge that this data can be generalized to the full system. Figure 4 presents the hydraulic control schematics for one leg of HyQ with servo-hydraulic and digital-hydraulic based systems. The supply pressure is provided by a variable displacement pump operating at 160bar and 25L/min. The hydraulic cylinders have a bore diameter of 16mm and stroke length of 80mm.



(a) Servo-hydraulic system for one leg



(b) Digital-hydraulic system for one leg

FIGURE 4 - HYDRAULIC SCHEMATIC FOR ONE LEG

To achieve walking and trotting motions the generalized parameters shown in Table 1 can be used. Simulations were run in the software package *LMS Imagine.Lab AMESim* to determine dynamic performance and compare results. *AMESim* is a multi-domain dynamic simulation software where hydraulic, mechanical, electrical and control sub-systems can be simulated.

TABLE 1 – PARAMETERS FOR TWO TYPES OF LOCOMOTION

Locomotion Type		Displacement of the Piston	Angular Displacement of the Leg	Frequency
Walking	Hip Joint	0.025m	40°	1Hz
	Knee Joint	0.05m	80°	
Trotting	Hip Joint	0.0125m	20°	1.6Hz
	Knee Joint	0.025m	40°	

Servo Valve System

For the servo valve system shown, Figure 4(a), a 4/3-way *Moog Type 30 Nozzle-Flapper Flow Control Servo valve* is utilized. The max rated flow, Q_{rated}, and internal leakage flow, Q_{leak} are 12L/min and 0.343L/min respectively at a rated pressure of 210bar. A full nonlinear valve-cylinder-connecting hoses dynamic model has been developed. In a linearized context the flow dynamic is approximated by a third order model [21]:

$$\mathrm{Q}(s) = \left[K_1 i - K_2 \left(\frac{\tau s}{1+\tau s}\right) \Delta P\right] \left(\frac{1}{1+\frac{s}{\omega n}}\right)^2 \tag{1}$$

where τ is time constant of the internal dynamic pressure feedback, ω_n is equivalent servo valve natural frequency, ΔP is the pressure drop through the valve, i is the differential current input to servovalve, K_1 is servo valve sensitivity to input current, and K_2 is the magnitude of the dynamic pressure feedback.

The natural frequency of the Moog valve is 200Hz, and the approximate step response time to 90% output is 0.0025s. One valve is used to actuate each joint, and two are needed for the whole leg.

Generalized motions from Table 1 were used for input commands, and position feedback control at the knee and hip joints based on a PID controller tuned to reduce position tracking error.

Digital Valve System

The simulation model for the digital valve system is based on *Sterling GS 0270* valves. These are high speed valves (relative to their flow rate) with a response time (open/close) of 0.01s. Their rated flow is 1L/min at a pressure of 5bar, maximum operating pressure 350bar, internal leakage 0.33mL/min (which is one order of magnitude smaller than the servo valve). An ideal digital on/off valve would have the following characteristic:

$$Q = \begin{cases} Q_{rated} & when\ x_{valve} \geq 100\% \\ 0 & when\ 0 \leq x_{valve} < 100\% \end{cases} \tag{2}$$

where x_{valve} is the displacement of the valve spool. However, in a real digital valve the flow rate would pass from zero to its rated value with a gradient depending on the valve geometry.

In the single leg each actuator is driven by four digital valves, so eight valves are needed for a leg. The feedback control system is similar to that of the servo hydraulic system where angular positions in the knee and hip are used with a PID controller utilizing stateflow based valve logic. PWM is then used to control the individual valves.

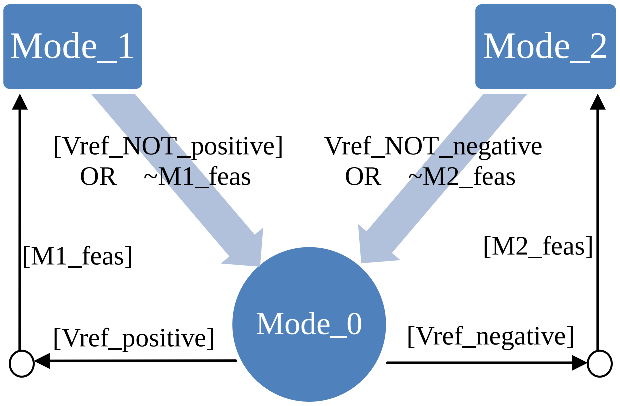


FIGURE 5 - STATEFLOW CHART OF THE DIGITAL HYDRAULIC CONTROLLER

Stateflow Based Controller for the Digital Valve System

To efficiently control position of the actuators, suitable combinations of valves are opened. A single PID controller is not enough for making optimal decisions with different valve configurations, so a higher level controller is required. Thus, a stateflow based controller [22] was developed to appropriately define the valve opening/closing sequence. This controller selects optimal valve configurations at each sampling time, taking into account pressure limitations, flow restrictions and motion types. Different operating modes are defined for all motion types that guarantees efficient performance can be achieved whenever necessary.

TABLE 2 – OPERATION MODES FOR DIGITAL VALVES

Operating Mode	Valve State (on/off)			
	Valve 1	Valve 2	Valve 3	Valve 4
Mode 0 – Stop	off	off	off	off
Mode 1 –Extend	on	off	on	off
Mode 2 – Retract	off	on	off	on

The stateflow chart that determines the running modes of the system is shown in Figure 5, and valve activation parameters are given in Table 2. In this model the three submodes are defined as followed:

Mode_0 is designed for stopped motion. If the reference speed, v_{ref}, is zero or close to zero, or no other mode is feasible, the mode is defined as the following function.

$$\begin{cases} \mathrm{Vref\_NOT\_Positive}(v_{ref}) \wedge \mathrm{Vref\_NOT\_negative}(v_{ref}) \\ \sim \mathrm{Mi\_feas}(F, P_S, \triangle\, P_{min}) \end{cases} \quad (3)$$

where the resulting signals will switch all of the valves, thus stopping the actuator.

Mode_1 is applied when the rod is extending. This mode is selected if the reference speed is larger than a threshold value, and the mode is feasible. In this condition valves 1 and 3 will be on, and valves 2 and 4 will be closed, and the mode condition is

$$\begin{cases} \mathrm{Vref\_positive}(v_{ref}) \\ \mathrm{M1}_{\mathrm{feas}(F, P_S, \triangle P_{min})} \end{cases} \quad (4)$$

Mode_2 executes retracting motion. This mode is similar to mode_1, but it involves movement in the opposite direction. In this case valves 2 and 4 will be opened and valves 1 and 3 will be closed. The mode is defined as

$$\begin{cases} \mathrm{Vref\_negative}(v_{ref}) \\ \mathrm{M2}_{\mathrm{feas}(F, P_S, \triangle P_{min})} \end{cases} \quad (5)$$

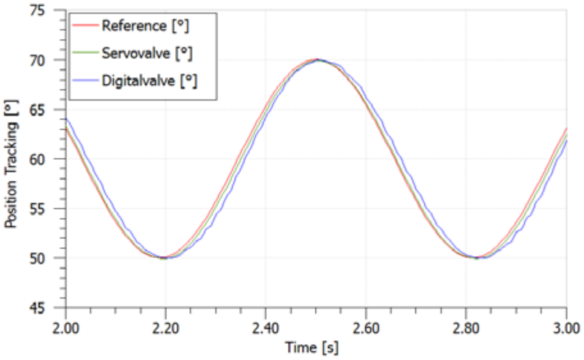
COMPARISON AND ANALYSIS OF THE RESULTS

Next we simulated the full leg utilizing digital and servo valve hydraulic actuation to compare displacement, flow and efficiency performance. This was done by giving the leg sinusoidal commands for generalized motions from Table 1. In future experimental testing will be completed to validate the full model.

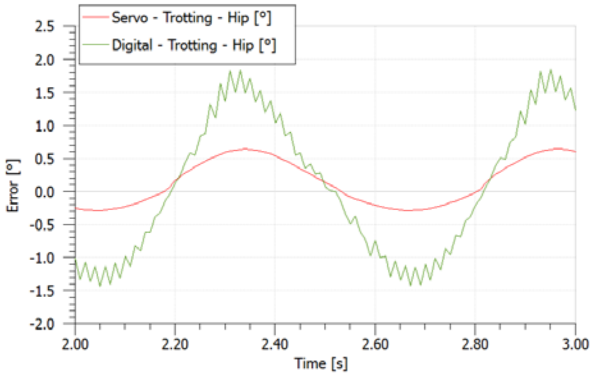
Position Tracking

Simulations were completed to compare position tracking capabilities of the digital system to the servo valve system. This is important because it shows the ability of the digital valve system to achieve similar motions to that of the high performance servo valve. Figure 6 (b) shows error response in the hip actuator to a generalized motion for trotting in servo and digital valve systems. It can be seen that the high performance servo hydraulic system achieves a greater accuracy than the digital hydraulic one. The maximum error for the servo system is 0.5°, while for the digital hydraulic system is 1.85°. Fluctuations in the digital system are due to the digital nature of the valves employed and can be reduced through improved controller design.

Similar performance results were found for other generalized motions in the hip and knee actuators. Overall it was found that the servo hydraulic system (Moog valve) shows maximum tracking errors of 1.4° for the hip, and 2.1° for the knee. The maximum tracking error of the digital system in the hip is 2° and on the knee is 3.2°. While the digital system (Sterling valve) is not currently as accurate as the servo system, further improvements to the position response of the digital system can be achieved through the use of faster responding valves, or changes to the control method.



(a) Position Tracking



(b) Error

FIGURE 6 - COMPARISON OF SIMULATED POSITION TRACKING FOR HIP ACTUATOR USING DIGITAL AND SERVO VALVE ACTUATION FOR A GENERALIZED TROTTING MOTION

Required Flow rate

Figure 7 shows simulated values for required flow averaged over 100 cycles for the servo and digital valve control systems when the leg is trotting. In the first half of the motion the leg is extending, and in the second half it is retracting. It can be seen that the required flow rate in the digital system is much lower than that of the servo valve system due to the lower internal leakage of digital valves. Similar results were found for walking motion where peak flow rates of 4L/min and 3.2L/min were found for extension and retraction respectively in the servo valve system, and the digital valve system displayed peak flows of 2.8L/min and 2.3L/min in extension and retraction.

If the resulting requirements for flow in a single leg are expanded into the full 4-legged HyQ robot during walking and trotting, a peak flow of 13.2L/min and 10L/min respectively for the servo valve based system is required. Alternatively, the digital system only requires peak flow rates of 8L/min and 5.2L/min during walking and trotting locomotion. This lower flow rate means a smaller pump, and therefore a smaller driving motor. Even though more valves are required this can still lead to significant power transmission weight and size savings, and thus increase robot autonomy.

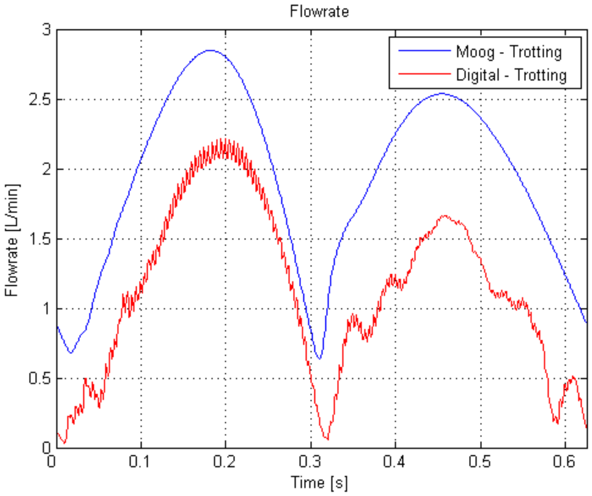


FIGURE 7 - REQUIRED FLOW RATE FOR TROTTING MOTION

Efficiency of Hydraulic Systems

Hydraulic power is the product of the differential pressure and flow rate [23], where the main energy losses are due to leakage, friction and orifice pressure drops. To determine efficiency across a valve the following assumptions are made:

1. The pump and relief valve are ideal without any leakage.
2. Minor energy loss from bends and fittings can be ignored.
3. The pump flow rate of the system is regarded as constant over time (flow ripple due to pump gears/pistons neglected).

The efficiency η of a hydraulic valve system is defined as:

$$\eta = \frac{\int_0^T P_L Q_L dt}{\int_0^T P_S Q_{SV} dt} = \frac{\int_0^T (P_1 - P_2)\cdot\frac{1}{2}(Q_1+Q_2)dt}{\int_0^T P_S(Q_S - Q_L)dt} \quad (5)$$

Load flow is calculated as:

$$Q_L = \frac{1}{2}(Q_1 + Q_2) \quad (6)$$

Load pressure is defined as:

$$P_L = P_1 - P_2 \quad (7)$$

where Q_S the supply flow at the outlet port of the pump, P_S the pressure upstream the valve system, Q_L the flow rate through the load, Q_{SV} the flow through the valve system, P_1 the piston side pressure, P_2 the rod side pressure and P_L the load pressure as shown in Figure 8.

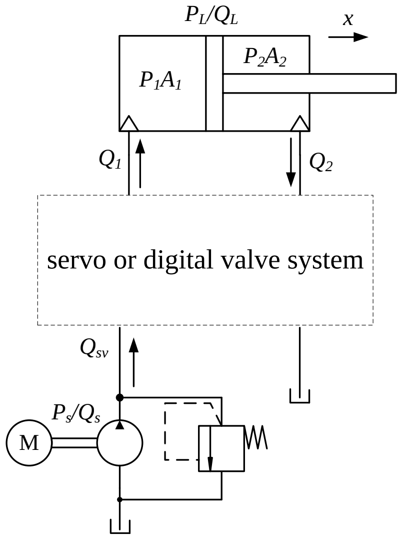


FIGURE 8 - BASIC HYDRAULIC SYSTEM

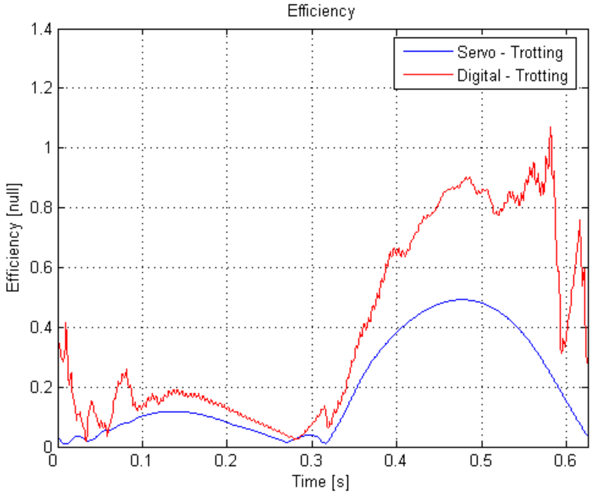


FIGURE 9 - COMPARISON OF AVERAGE EFFICIENCY BETWEEN SERVO AND DIGITAL SYSTEMS FOR A FULL LEG CYCLE DURING TROTTING MOTION

Figure 9 shows a comparison of the full leg system efficiency for the servo and digital hydraulic valve configurations utilizing a generalized motion for trotting. In the first half of the motion the leg is extending, and in the second half it is retracting. It can be seen that for trotting motion the Moog servo valves show peak efficiencies of about 12% and 50% for extension and retraction respectively. Alternatively, for the same motion the digital hydraulic system shows efficiencies of

20% during extension, and 90% when retracting. Fluctuations in the digital valve efficiency values are likely from pressure fluctuations due to fluid compressibility in the simulation when the valves open/close quickly. As shown in the position results these fluctuations have little effect on system response due to the second order nature of the mechanical system. The spike in efficiency above 100% at 580ms is numerical in nature, and is due to a sudden increase in pressure at constant input energy.

For walking motion it was found that the servo valve system achieved maximum efficiencies of 11% in extension and 55% in retraction. While the digital valve system achieved efficiencies of 20% and 90% in extension and retraction respectively.

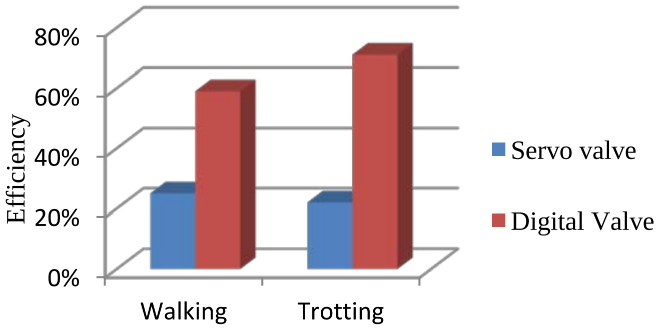


FIGURE 10 - COMPARISON OF TOTAL EFFICIENCY OVER 100 CYCLES FOR GENERALIZED WALKING AND TROTTING MOTIONS IN THE FULL LEG

A summary of the total efficiency over 100 cycles is provided in Figure 10. When the leg utilizes a generalized motion for walking the digital valve based system achieves an overall efficiency of 59%, while the Moog servo valve based system achieves and overall efficiency of only 25%. For trotting the digital system achieves overall efficiency of 71%, while the servo valve system only achieves an overall efficiency of 22%. This means that the servo valve system uses significantly less power from the pump to drive the system, and the remaining energy is wasted and converted into heat.

CONCLUSIONS

In this paper digital hydraulic actuation is applied to a quadruped robot leg and compared to a traditional servo actuation system based on high performance Moog valves. The results show similar position tracking performance from the digital system compared to that of the servo hydraulic system. While the digital hydraulic system presents position tracking errors slightly larger than those of high performance servo hydraulic systems, it is still a practical solution for typical walking and trotting applications.

It was also shown that the digital hydraulic system reduces the required flow rate. However, the real advantage of digital valves is in their significantly greater efficiency over traditional servo valve systems, due to their lower internal leakage. The increased efficiency would allow for the use of smaller pumps and motors to provide flow to the system, which in turn reduces the size and weight of the required hydraulic supply.

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